New developments to integrate ground risk management from concept to completion

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ABSTRACT: Tunnelling projects that fail to meet the planned objectives of time, cost, or quality are often a result of unanticipated and unpriced geotechnical risks at the tender stage. Reliance upon geotechnical interpretations and baselines without considering uncertainties in, and variations from the interpretations and baselines can lead to the project team (Owner, Designer and Contractor) to be collectively unprepared. Assessing and quantifying the range of uncertainty in ground properties and behavior can improve risk management, minimize commercial losses, and enhance confidence in tunnelling projects. The quantification of geotechnical uncertainty using geostatistical methods provides a practical means to improve risk management and can now be used throughout planning, procurement and construction. This paper highlights new developments on the application of geostatistics and data-driven decision making, putting the focus back where it needs to be, to use Sir Alan Muir-Woods' words, on the 'old enemy' the ground itself.

1 INTRODUCTION

As the ground conditions are the dominant factor upon most of the decisions made when planning, designing or constructing tunnels, all tunnelling projects must face uncertainty in terms of the differences between the necessarily simplified models described at tender and the reality of full-scale construction. The gaps between pre-construction phase assumptions and the actual responses to construction require continual technical, commercial and communication attention.

It is generally accepted that the onus is upon the client organisation ('owners') to document and communicate intrinsic and extrinsic geological variability, stratigraphic variation, the spatial variation in geotechnical parameters, the differences between laboratory sampling/testing and in-situ behavior, groundwater variations, and the presence and nature of anomalies such as boulders, voids, intrusions or fault zones as part of the tender process. This remains one of the most significant procurement challenges with principal reliance upon 'reference conditions' or 'geotechnical baselines' in a Geotechnical Baseline Report (GBR).

ISO 3100 highlights the following for client organisations:

1. Understand the risks facing the organisation in pursuit of its objectives (e.g., a successful project).
2. Ensure that project risks are adequately considered.
3. Ensure that such risks are appropriate in the context of the orgainisation's objectives.
4. Ensure that information about such risks and their allocation is properly communicated.
5. Ensure that systems to manage risks will be effective.

It follows that the risks, including geotechnical risks, a client organisation is willing to retain, fully allocate or share with the contractor must be quantified and contingency sums identified as part of the planning process.

Note also the following from Shapiro (2010):

> *'Risk tends to be allocated on the basis of commercial and negotiating strength. Although not always the best way to proceed, the stronger party will often allocate risk that it does not want to bear to the weaker party. This scenario does not necessarily provide the most effective and efficient risk management process. Improperly-allocated risks will have an impact on the entire project and may affect the stronger party as well as the weaker.'*

Abrahamson (1978) stated that to achieve a fair and equitable allocation of the risks inherent in a construction project, a risk should be allocated to a party if:

- The risk is within the party's control;
- The party can transfer the risk, for example, through insurance, and it is most economically beneficial to deal with the risk in this fashion;
- The preponderant economic benefit of controlling the risk lies with the party in question;
- To place the risk upon the party in question is in the interest of efficiency, including planning, incentive and innovation; and/or
- As the risk eventuates, the loss falls on that party in the first instance and if not practicable, or there is no reason under the above principles, to cause expense and uncertainty by attempting to transfer the loss to another.

We emphasize much caution in relation to the principle of risk transfer above given that the insurance industry has clearly responded to its modern role reflected in the of ITA/IMIA Guide of 2023, viz '...insurance is not a Control or Risk Treatment measure', in the interests of offering a sustainable insurance market. We further note that the transfer principle may be economically inefficient when geotechnical risks are wholly transferred from Owners to Contractors (or sub-Contractors) unless the risk has been properly priced and considered, i.e., sufficient tendering resources have been allocated and accepted in the bid. It is our experience that often a risk is transferred because it is convenient or expedient, and unfortunately sometimes not very well understood and thus risks are under-resourced especially under a competitive price weighted contest.

We further note that exculpatory transfer of risk – full ground risk transfer such as is typically adopted in PPP procurement results in higher relative bid costs that may or may not eventuate, thus unnecessarily increasing project costs. Even if such contractual risk transfer is effective, the quality of risk management can suffer as shown by several recent, large tunnelling losses. Therefore, notwithstanding the economic inefficiency, the transfer of risk can be illusory; an ambulance at the base of a cliff, as opposed to a fence at the top. We have a collective interest in the perception of the industry, and confidence and reputation suffers when projects fail, impacting us all, usually when financing is being sought for the next tunnelling project.

Consideration of the above raises the following fundamental questions:

- How uncertain is our knowledge of the ground?
- Despite contractual provisions, who ultimately bears the risks and what are the risks arising from a protracted dispute regarding losses, and *cui bono*?
- When would greater certainty, or quantified uncertainty become useful?

By establishing uncertainty parameters, the setting of geotechnical interpretations and/or baselines will be more transparent and the need for further mitigation or investigation understood. In pre-tender, the client can inform the level of further investigation and contingency. When bidding, tenderers can understand their exposure better and, upon receipt of offers, the client can assess the quality of the bids in respect of geotechnical risk management resources. During construction, any prior assumptions can be verified before they become losses.

There is always significant pressure when drafting a GBR to get things 'right' in terms of encompassing the range of material risks and defining limits of material strengths and behaviour, etc. and this can lead to some unhelpful, ambiguous representations that do not help to avoid disputes should things turn out to be more adverse than originally assumed. In fact, such ambiguity can be very counter-productive to the Owners interests given the principle of 'contra proferentum'.

Most representations of the geology and geotechnical condition for a tunnel alignment are deterministic in that they derive a single interpretation despite spatial variability and decreasing ability to correlate conditions with increasing separation between investigation points (see Phoon et al. 2022). There is typically no quantification of accuracy or consideration of bias (see Kahneman 2011) although sometime ranges are presented. The uncertainty in the interpretation(s) is seldom quantified. Sources and types of uncertainty, the impact these uncertainties may have on contract risk allocation, and approaches for managing risks associated with these uncertainties are outlined in the next section.

When adapted for specific project circumstances, this should give more clarity to the degree of uncertainty present to enable decisions to apply greater resources to either reduce the uncertainty (typically with further investigation) or mitigate the risk using other means (modifications to design, or construction method or both) as necessary. This is considered a more equitable way of doing things, i.e., to promote proper understanding of geotechnical risk and to quote CIRIA 79, 'the promotion of equity in the tunnelling field…should lead to increased efficiency and reduce cost.', a worthy goal for any tunnelling project.

2 UNCERTAINTY IN GEOTECHNICAL INTERPRETATION FOR TUNNELLING

2.1 *Uncertainty types and sources*

Uncertainties related to subsurface conditions generally fall under three categories (Phoon and Kulhawy 1999; Baecher and Christian 2003; HelmHoltz UQ 2023):

a. *Natural* or *Aleatory* Variability – The inherent spatial and temporal randomness in geologic materials. In principle, this cannot be reduced; however, the degree of variability can be estimated more accurately by collecting more data.
b. *Knowledge* or *Epistemic* Uncertainty – Includes: (i) statistical estimation and site characterization uncertainty. (ii) model uncertainty and (iii) parameter (or measurement) uncertainty. This type of uncertainty is related to the lack of sufficient information.
c. *Ontological Uncertainty* - arising from either semantic uncertainty when different meanings are ascribed to the same terms or definitions lack clarity, or from interpretational uncertainty, where data decoding methodologies and their reliability limits are not clearly defined or are subject to inevitable human bias.

While it is generally accepted that these uncertainties will exist, too seldomly are they properly quantified and the implications for risks assessed. Inadequate assessment of subsurface variability and uncertainty on a project basis can often lead to critical errors in geological and geotechnical interpretations.

2.2 *Impact of uncertainty on ground investigations*

It is often said that 'the client pays for sufficient site investigation, whether it does one or not'. With limitations of access in all tunnelling contexts there are often severe limitations on the data available for interpretation. The significance of the resulting geotechnical uncertainty is usually unknown as it is typically not quantified nor communicated. Therefore, it is recommended to quantify the uncertainty of the subsurface conditions from site investigations to determine a measure of the 'sufficiency' of the ground investigation along the alignment. This can also make clear the need for more site investigation, sampling and testing.

In 1984 the U.S. National Committee on Tunnelling Technology (USNCTT) following a comprehensive review of 200 projects, recommended that "Expenditures for geotechnical site exploration should be increased to an average of 3.0 percent of estimated project cost, for better overall results" (National Research Council, 1984). As a guide to the scale of investment into ground characterisation, it is a useful starting point and more significant in locations where there has been little or no tunnelling.

2.3 *Communicating the Risk*

Incorrect geotechnical assumptions are often the main source of commercial losses and even catastrophic failures. Several case studies of geotechnical challenges or failures in tunnel construction partially or entirely linked to inadequate geotechnical interpretation can be referenced (e.g., De Sousa and Einstein 2021, Tonks et al., 2017). If a deterministic model is available, probabilistic analysis can provide additional insights, especially in the context of sensitivity analysis for geotechnical problems (Lacasse and Nadim, 1998) and in relation to geotechnical baselines, probabilistic methods can:

- Quantify the probability of exceeding baseline conditions.
- Identify the most probable response through metrics such as the reliability index.

Nevertheless, it is essential to validate pre-construction assumptions such as geological transitions and fault zones as part of ongoing risk management during construction to ensure that the mathematics remain 'grounded' in observed site conditions.

We note that the ability to look ahead of the advancing tunnel is improving with the use of horizontal seismic profiling (see Nilot et al 2023) and other geophysical techniques such as muography (see De Sloverre (2024) and Steer and Thompson (2024)). The prior use of probabilistic geotechnics allows for a more informed view of where enhanced risk management measures and interventions such as advanced geophysics or more conventional measures should commence.

The degree to which the parties to a contract understand the project risks at the time of forming the contract is considered a fundamental 'success factor' for any tunnel project and is related to the third category of uncertainty defined above. This understanding is essential in order that:

- Risks (not just geotechnical risks) are clearly allocated,
- Financial provisions are made accordingly, and
- The parties understand the basis for changed conditions (from 'reference conditions' created by the GBR baselines) should they arise, and thereby minimize the potential for dispute.

An approach of quantifying uncertainty should be valuable to any client organization that is committed to the efficient management of risk in underground construction and in determining and allocating resources to manage such uncertainty.

3 QUANTIFYING UNCERTAINTIES USING GEOSTATISTICAL METHODS

This section introduces some applications for quantifying uncertainty in geotechnical interpretations (both ground properties and behavior) using geostatistical methods. Readers should refer to other references for a more detailed discussion of the theory and methods (e.g., Chiles and Delfiner 2012, Pyrcs and Deutsch 2014).

3.1 *Overview of geostatistics*

Geostatistics is a class of applied statistics used to analyze the spatial relationship of data to make predictions at unsampled locations. Widely adopted in other industries such as natural resources, mining and hydrogeology, it is considered the best approach to model the spatial distribution and variability of geological and geotechnical properties. It provides a framework to integrate data from many sources (e.g., geological interpretation, direct measurements and secondary measurements/information). The method is practical (consistent with the data), repeatable and can easily be updated as additional information is obtained.

In a simulation framework, multiple predictions (or realizations) of the geological/geotechnical conditions are derived from the existing information to approximate the range of possible 'scenarios' according to the data. The variability among the derived scenarios is the basis for the quantified uncertainty. These scenarios can then be evaluated for the corresponding ground behavior as a result of tunnel construction, providing a means to quantify the risk (due to geotechnical uncertainty) and developing mitigation measures to minimize the probability of 'failure.'

3.2 *Spatial uncertainty evaluation for geological boundaries*

Spatial uncertainty associated with geological interfaces is important to characterize, especially if these are significant with respect to excavation management, other requirements, or third-party impacts to highlight when additional investigations may be advantageous. Figure 1 illustrates a section where the spatial uncertainty between different geologic units is quantified, and zones of high potential for mixed face conditions and transitions between units.

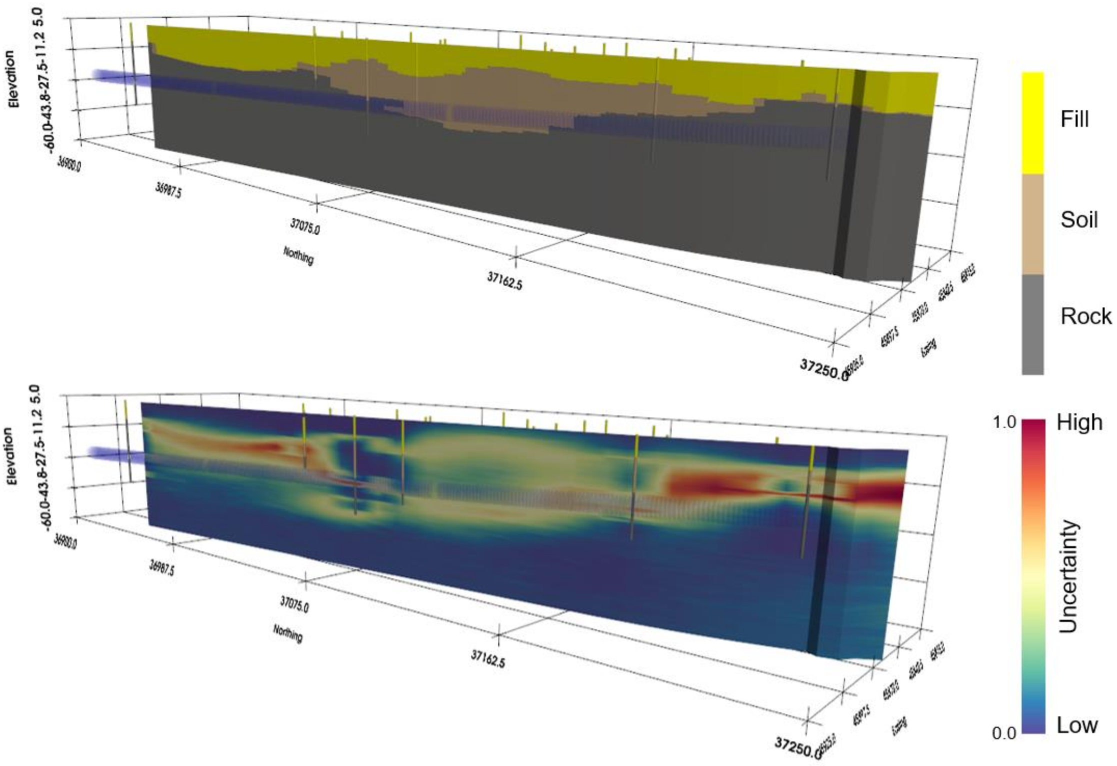

Figure 1. Tunnel long section illustrating a deterministic geological profile (top) and the uncertainty in transitions between different geologic units (bottom).

3.3 *Face support pressure and ground deformation*

Uncertainty in stratigraphic transitions and variability of geotechnical parameters within geologic units often leads to uncertainty as to the effectiveness of support mechanisms to control ground deformation. In a geostatistical simulation framework, each scenario can be input into a numerical model to simulate the tunnel excavation sequence and face support pressure to estimate the range of resulting ground deformation. Figure 2 presents the predicted longitudinal settlement troughs for one ground surface settlement monitoring location with an assumed face support pressure. The reference prediction (red) is based on the deterministic design geotechnical parameters and the geostatistical predictions (blue) are from the multiple scenarios of the geostatistical simulation. It can be observed that the reference prediction underestimated the observed settlement (black) by a factor of two, whereas the observed settlement falls within the distribution of the geostatistical predictions. One can use this approach to optimize ground support, in view of the geological/geotechnical uncertainty.

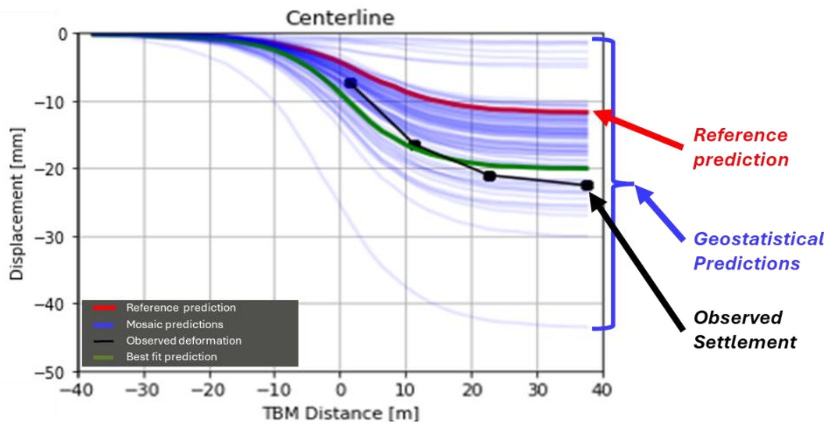

Figure 2. Longitudinal settlement troughs: Reference prediction (red), geostatistical predictions (blue), observed settlement (black) and best fit prediction (green).

3.4 *Tool wear and clogging potential*

Two geotechnical risks to the operational efficiency of a tunnel boring machine are tool wear and clogging potential. The variability in abrasivity and consistency of the excavated ground can have significant impacts on the tool wear rates and clogging potential, respectively.

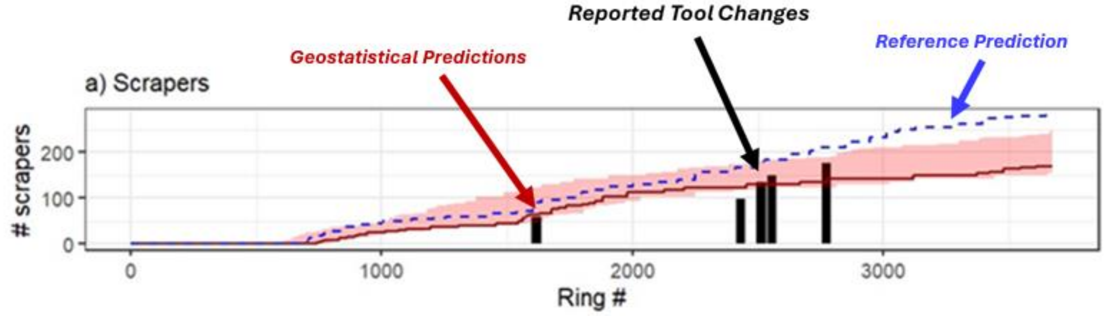

Figure 3. Estimated cumulative number of cutting tools to be replaced.

Figures 3 and 4 illustrate example outputs for tool change estimates and soil conditioning to mitigate clogging, respectively. Rather than being forced to rely on a single 'best' estimate, the geostatistical analysis enables one to evaluate the range of possible outcomes and plan mitigation measures accordingly.

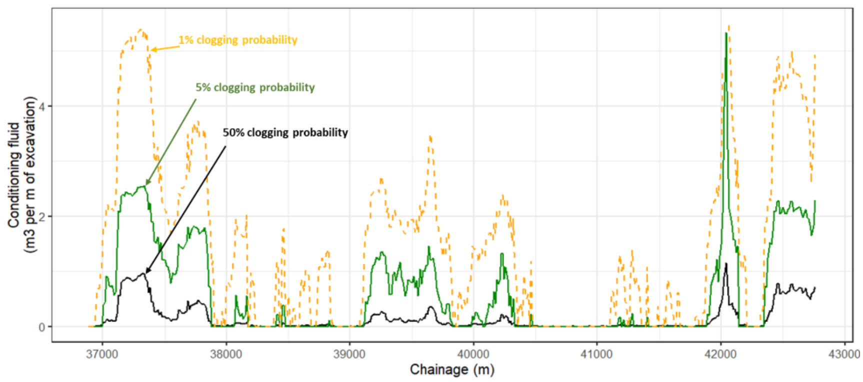

Figure 4. Volume of conditioning fluid injection required for various degrees of clogging probability.

3.5 *Penetration rate and TBM utilisation*

Penetration rate models are a small component of actual TBM utilisation. For TBM tunnels in rock, transition zones and exceptional conditions that require modification such as fault zones, water ingress, abrasive or gassy ground may significantly influence TBM utilisation. For soft ground TBM tunnels, advance rates are typically dominated by logistics.

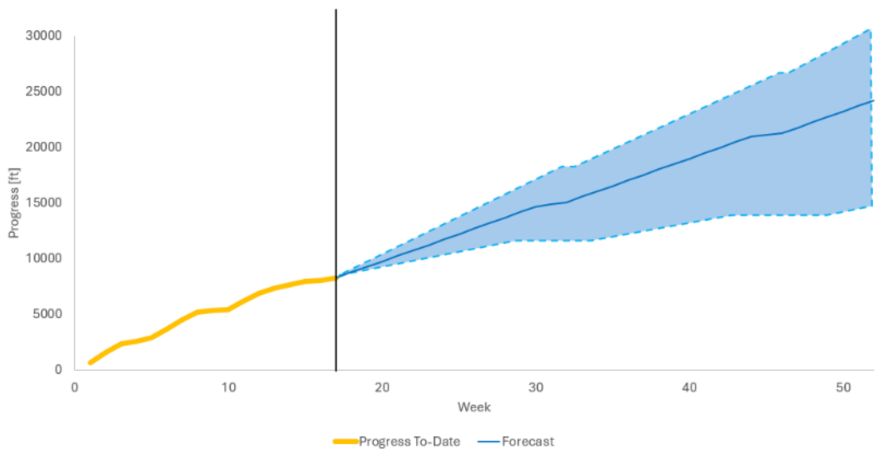

Figure 5. Forecasted progress schedule based on penetration rates and utilization.

Nonetheless, geostatistical simulations can be used to evaluate the influence of geotechnical variability and uncertainty on penetration rates and those elements of geotechnical risk that may affect production schedules such as the location of mixed ground and the impact and likelihood of fault zones etc. In this way, ground risks typically owned by clients (and allocated via GBRs) can be separated from efficiency risks which are typically and properly assigned to the Contractor.

Figure 5 presents a progress timeline considering the uncertainty in penetration rates and a simplified model for utilisation. Projections can be updated throughout construction as uncertainties in penetration rates and utilisation factors impacted by geotechnical risks are reduced.

3.6 *Reducing uncertainty through observations*

Data collected during construction (instrumentation and monitoring, machine data, observation records) provides a means to routinely update the geostatistical ground model through the lifecycle of the project. Figure 6 illustrates the benefit of doing this with settlement data. As actual settlements are recorded, these are used to back analyze the true in-situ parameters, which is then used to update the ground model and subsequent predictions. This significantly improves prediction accuracy and reduces uncertainty.

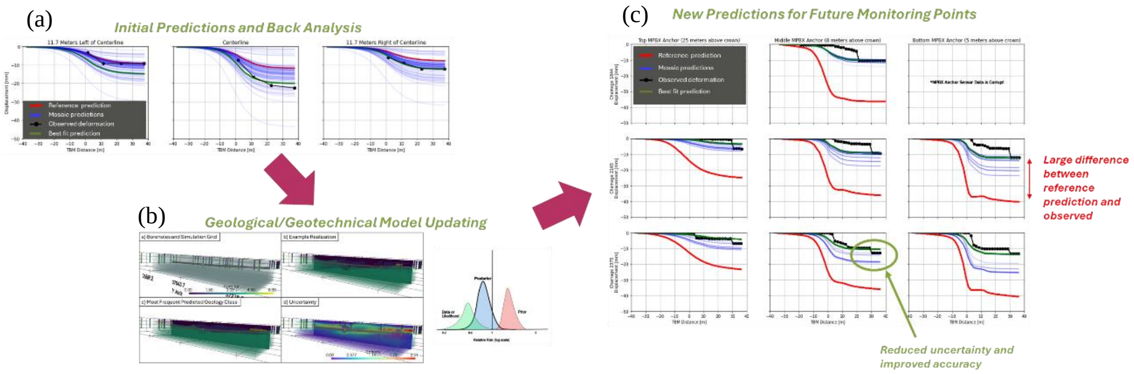

Figure 6. Using observations and recorded data to update the ground model and predictions, resulting in improved accuracy and reduced uncertainty. (a) Observations (e.g., recorded ground deformation) are compared with initial predictions to back analyze geological/geotechnical parameters using genetic algorithms. (b) The back analyzed parameters are incorporated into the ground modeling routine to update the geological/geotechnical model. (c) The updated geological/geotechnical model is then used to update predictions for future monitoring points ahead of the excavation face, which often results in significantly reduced uncertainty as a result of the improved understanding of the ground conditions and behavior.

4 CONCLUSIONS

Whilst geotechnical risks are not the only source of risk in tunnelling, they tend to dominate decision making at every stage of development. Usually when projects suffer commercial losses it is because key risks have not been anticipated and priced at tender, or commercial close. As a result of under-sourcing, and in the absence of a rational basis to understand the uncertainty of the ground along an alignment, the project team (Owner, Contractor and Designer) may be very unprepared for the situations that they encounter.

A focus on effective risk management should enable projects to positively differentiate themselves in the ongoing competition for resources and a more sophisticated risk management approach should be reflected in the number and quality of tenderers or proponents. By moving away from purely deterministic geotechnical interpretations and emphasizing uncertainty quantification, all parties will be better informed and prepared.

As not all jurisdictions allow it, if there is no opportunity for tender interaction (i.e., ‘interactive tendering’), it becomes even more important to communicate the limitations of understanding and the evidential basis to the extent practicable, including the examination of uncertainty and the potential for bias.

A geostatistics based approach for quantifying uncertainty can be implemented at all stages of the project: planning, ground investigations interpretive reporting and GBR preparation, bidding at tender, procurement and GBR negotiations, and construction.

This paper presents a way of improving the management of geotechnical risk using well established techniques applied in a systematic way to establish the adequacy of the geotechnical model used as a basis of foreseeability (via GBR baselines) for the Contract so that the Contractor may commence the project with sufficient resources and the knowledge that anything 'unforeseen' can be efficiently dealt with.

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